OPERATION AND CALIBRATION OF MRL PERMEAMETER FOR MEASUREMENT OF DC MAGNETIC PROPERTIES OF MATERIALS UNDER STRESS

(4)

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Abstract

This note describes the operation and calibration of experimental apparatus constructed at MRL for the measurement of the DC magnetic properties of steels. The instrument is capable of measuring normal induction curves and hysteresis loops at applied magnetic field strengths up to about 1 kA/m. A special feature is the ability to apply mechanical stress to the specimens before or during magnetic measurements. The stress and magnetic field are applied in the same direction in the specimen, and the magnetic induction is also measured in this direction.

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1. Introduction

The instrument described in this note was built to enable Materials Research Laboratory (MRL) to measure the effects of stress and stress fluctuation on the DC magnetic properties of various steels. Standard permeameters are available for the measurement of magnetic properties in the absence of stress (see ASTM test methods A341, A596 and A773). However, there is no standard for the measurement of these properties under stress. Therefore a purpose built device was required.

The MRL permeameter was constructed in early 1989. The details of the electronic design together with methods of improving the performance are recorded in the Appendix. The instrument is essentially a prototype, and as such there are certain idiosyncracies not normally encountered when using a scientific instrument. It is important that an operator be aware of potential pitfalls and the steps necessary to obtain reproducible results. To this end, this note describes the calibration procedure and mode of operation of the MRL permeameter.

2. Apparatus

2.1 Overview

The complete apparatus consists of five main components as follows:

(i) A Riehle tension/compression testing machine for applying loads to the test specimens. To date only compressive loads have been used. Minor modifications would be necessary to enable the effects of tensile stresses to be examined.

(ii) Electronic circuits for applying known H fields and measuring the resultant B fields induced in the specimens by means of coils wound on the specimens. The B field is measured by integration of the emf induced in the B coil as a result of changes in the current supplied to the H coil. (The electronics for such integrators are described in ASTM, 1989; ASTM, 1973). Separate provision is made for demagnetizing the specimens using the H coils.

(iii) A magnetic circuit consisting of two identical test specimens connected by two soft iron yokes (machined from a rimming steel ingot) as shown in Figure 1. The B and H coils are wound on formers, allowing different test specimens to be inserted. The specimens are preferably long and thin to avoid demagnetizing factor effects, but are also preferably short and squat to avoid buckling under compressive load. The specimen dimensions selected represent a compromise between these requirements. The specimens are magnetically insulated from the testing machine platens with sheets of austenitic stainless steel.

(iv) A third steel rod of the same dimensions as the magnetic specimens, arranged as shown in Figure 1, to increase the mechanical stability under compressive load. This rod is not part of the magnetic circuit, and would not be required for tests under tensile load. Holes drilled in two aluminium plates locate the three steel rods. A small aluminium slug is placed on the loading machine platen at the centroid of the triangle formed by the three rods, to eliminate any misorientation of the platens and ensure that each steel rod carries the same load.

(v) An X-Y recorder for plotting changes in B against stress or H field (the Riehle control box has an analogue voltage output of 1 V for full scale load deflection). Digital voltmeters can be used in place of the XY recorder which is susceptible to power supply voltage spikes.

This arrangement eliminates the sliding magnetic contacts necessary in some experimental arrangements due to contraction under stress (e.g. Craik and Wood 1970). The design is based on the Burrows permeameter (Spooner, 1927) and is similar to the arrangement used by Lliboutry (1951). Other instruments designed for similar purposes include those described by Schneider and Semcken (1981), Pravdin et al. (1982), Jiles et al. (1984), and Ara (1989).

2.2 Test Specimens

The specimen dimensions selected were 10.25 mm diameter by 210 mm length. The diameter was selected to be fractionally less than the internal diameter of the former (tube) on which the coils were wound. The length (ideally as long as possible) was restricted to 210 mm to ensure that the Euler buckling load was safely avoided at a maximum compressive stress of 500 MPa.

It is important that the length of the three steel rods be closely matched so that the compressive load is shared equally between them (210 ± 0.1 mm). The stress can then be calculated by simply dividing the load indicated on the testing machine by three. The small aluminium slug in Figure 1 helps to compensate for any slight differences in length. The diameters of test specimens should also be carefully controlled, both for equal load distribution and to ensure good contact with the soft iron yokes (10.20 - 10.25 mm).

2.3 Coils

The basic philosophy of the Burrows permeameter and the MRL apparatus is to have a complete magnetic circuit and therefore uniform H field in the specimens. Although only four coils (one H coil and one B coil per specimen) are strictly required, a more uniform H field is achieved by the use of eight additional coils as described below. The arrangement of the coils is shown in Figure 2. They consist of the following:

(i) The primary H windings have 298 turns on each specimen and occupy the full 150 mm distance between the iron yokes. The two coils are connected in series (assisting).

(ii) The main B coils are wound on top of the H coils near the centres of the specimens where the H field is most uniform. There are 3000 turns on each specimen, and the coils are in series as for the H coils.

(iii) To ensure a more uniform H field in the specimens, supplementary H coils are wound over the main H coil at the ends of the main H coils adjacent to the yokes. The coils are connected in series assisting the main H coils. They compensate for the reluctances of the yokes and the junctions between specimen and yoke.

(iv) For the MRL instrument, the current in the H compensation coils is proportional to that in the main H coils. In order to determine the proportionality constant, supplementary B coils of 1500 turns each are wound at each end of the main B coils (3000 turns each). These are connected in series with each other as for the H compensation coils. When the H field is uniform in the central part of the specimens, the emf measured by the two main B coils (together) should exactly match that of the four supplementary B coils. The current through the supplementary H coils is adjusted so that this is the case.

Ideally the H compensation should be set for each H field, but to simplify the electronics the MRL device maintains the H compensation current in proportion to the H coil current. Once the compensation level is set using the supplementary B coils, measurements are carried out using just the main B coils.

It is important to insulate the ends of the coil assemblies from the iron yokes when assembling the magnetic circuit to avoid electrical short circuits.

2.4 Controls

The MRL apparatus allows the change in B value to be recorded (by integration) as the H field is changed in a number of ways as follows:

(a) manually changing the H coil current,

(b) automatically ramping up the H coil current (linear increase with time) at a preset rate,

(c) automatically ramping the H current up and down between preset limits (i.e. a triangular waveform) at a preset rate.

In all cases the H compensation current increases in proportion to the main H coil current.

The front panel controls are shown schematically in Figure 3. The main features are as follows:

(i) Output sockets for B and H with voltage proportional to B and H in the specimen.

(ii) **Integrator Switch.** The integrator is reset to zero when this switch is turned to the "Reset" position. The integrator begins to integrate the rate of flux change ($d\phi/dt$) and output a voltage proportional to B when switched to the "Run" position.

(iii) **Selector Switch.** Allows the operator to select the demagnetize mode or select the desired method of changing the H field (one of the three methods (a)-(c) described above).

When set to "DC" the H field is controlled by manually setting the DC control potentiometer (point iv).

When set to "Ramp" the H field is under control by the Ramp Control (point v).

When set to "Triangle" the triangle waveform is applied as soon as the Integrator switch is set to "Run". The amplitude of the wave is determined by the Triangle Amplitude control (point vi).

(iv) **DC Control.** This ten turn potentiometer allows manual control of the H field. Unlike the triangle wave it becomes effective immediately the selector switch is set to DC (does not require the integrator switch to be set to "Run").

(v) **Ramp Control.** This switch has three positions, a "Reset" position which returns H to zero, a "Ramp" position in which H rises linearly at a preselected rate, and a "Hold" position in which H is maintained at whatever level it has ramped up to.

(vi) **Triangle Amplitude.** This control sets the amplitude of the H field triangle waveform.

(vii) **Compensation Selector Switch.** This is set to "Run" during normal operation but is set to "Comp" to allow the H compensation coil setting to be adjusted (see viii). In the "Comp" position the B output is no longer B itself but is the difference (ΔB) between B as measured by the main B coils and B as measured by the supplementary B coils.

(viii) **Compensation Adjustment.** This ten turn potentiometer controls the amount of current in the H compensation coils (always proportional to the main H coil current). It is adjusted when the Compensation Selector Switch is in the "Comp" position so that the output is minimized. (When the integrator is turned to "Run", a triangle H waveform is applied with amplitude controlled by the Triangle Amplitude Control. The compensation adjustment is made to minimise the range of ΔB during a cycle as discussed further in 3.1). Compensation is zero with the control in the fully clockwise position and reaches a maximum at the fully counter clockwise position.

Additional controls behind the front panel include:

1. Ramp rate or speed control variable resistor sets the ramp rate in both Ramp and Triangle modes. Clockwise rotation increases the ramp rate.

2. Drift control ten-turn potentiometer allows fine adjustment to eliminate drift in the integrator. Drift is a major problem in this type of instrument. Even tiny temperature

fluctuations cause the integrator output voltage to drift. The electronics should be allowed about twenty minutes to warm up before beginning measurements. Drift is more noticeable if this is not done.

2.5 Demagnetization

Demagnetization is carried out by applying a sinusoidal waveform to the H coils and slowly decreasing its amplitude to zero. It is quite difficult to achieve complete demagnetization of the specimens. With the Selector Switch set to "Demag" and the Integrator Switch on "Reset", the AC magnetic field is applied in one of two ways:

(i) A variac connected to the 50 Hz power supply and connected to the H coils via a step down transformer. The voltage is manually increased to 240 V and then decreased to zero.

(ii) A BWD 602 Combination Instrument (combination waveform generator and power supply) similarly connected to the H coils via the transformer. A low frequency sine wave is applied, with the amplitude again under manual control.

A diagram depicting the electrical connections is shown in Figure 4. The variac method is ineffective when the specimens are connected by the yokes because of the high frequency and consequent eddy currents in the specimens. It is reasonably effective when the specimens are simply placed symmetrically in the coils without the connecting yokes, but still leaves slight residual magnetization. The low frequency waveform generator is required for more complete demagnetization. However, it is important to initially use the variac method if the specimens have become strongly magnetized.

Demagnetization using the Combination Instrument is basically the same as with the variac, but it can be carried out with the magnetic circuit fully assembled. A frequency of 2 Hz is usually selected and the amplitude slowly increased to the maximum available and then decreased to zero. The rate of change of amplitude must be correspondingly small because of the low frequency.

When working at low field strengths, the effect of incomplete demagnetization becomes apparent in the change in magnetization due to stress cycling. For the same stress, the change in magnetization should be of the same magnitude (but opposite sign) for H fields of +h and -h. Lack of symmetry indicates incomplete demagnetization. Application of stress to a fully demagnetized specimen should cause no change in magnetization. The demagnetization can be improved by reversing the orientation of one of the specimens after variac demagnetization as the residual magnetizations of the specimens then oppose each other in the magnetic circuit.

3. Calibration

The first step in calibrating the instrument is to correctly set the H compensation coil current (in proportion to the main H coil current). Once this is done the actual calibration of the H and B output voltages can proceed. The H compensation should not be changed after calibration.

3.1 Compensation Adjustment

The procedure adopted for compensation adjustment is as follows:

(i) Set Compensation Selector Switch to "Comp".

(ii) Set triangle wave amplitude to about 1000 A/m (± 500 A/m), or the desired working range.

(iii) Turn Integrator Switch to "Run" and plot ΔB against H as the triangle waveform is applied.

(iv) Adjust the compensation control so that the tips of the hysteresis loop are at the same level. The ΔB value is then as small as possible over the full range of H values.

Examples of the hysteresis loops for a particular steel specimen are shown in Figure 5. Unless the integrator drift has been corrected the loops may not be closed. To date the compensation has been set at the midrange of the control potentiometer (five full turns anticlockwise from the zero position).

3.2 H Field Calibration

The H and B fields have been calibrated using a specimen whose magnetic behaviour is well characterized (by measurement at the CSIRO Division of Applied Physics). A preliminary calibration was carried out by direct calculation from the coil characteristics.

To a first approximation, the magnetic field in the specimens due to the H coil current is:

$$H = NI/\ell = 2000\,I \qquad (1)$$

where H is in A/m, N is the number of turns in the coil, I is the coil current in A and ℓ is the length of the specimen between the yokes in m. Because of the magnetic softness of the iron yokes and their large cross section they offer low reluctance to the magnetomotive force and exert little influence on the H field in the specimens (unless the specimens themselves are very soft). See for example Ramanowitz (1971). However, the actual H field is larger than this because of the H compensation coil current.

Final calibration of the H field was carried out by measuring the normal induction curve of the well-characterized specimen. Extrapolating the most steeply rising part of the induction curve to the H axis gave an intercept of about 500 A/m. This was compared with the intercept for the CSIRO measured curve. A variable resistance in the electronics was then adjusted so that the two intercepts were equal, making 1 volt of output at the H socket on the control panel equivalent to 1 kA/m of H field. A different calibration would be required for different H compensation settings.

3.3 B Field Calibration

The axial component of the B field at the centre of a thick-walled coil (Zijlstra, 1967) produces a flux of

$$\phi = \pi NB\,(r^3_2 - r^3_1)\,/\,3(r_2 - r_1) = N\pi r^2 B \tag{2}$$

where N is the number of turns, r_1 and r_2 are the inner and outer radii of the coil and r is the effective radius of the coil. For the MRL B coils, r is 8.7 mm and N is 6000.

This is the flux which would be measured if the specimen filled the internal cross section of the coil. Because the specimen and B coil are separated by the coil former and the H coil there is an "air" flux correction. The actual flux level (ASTM 1989) is

$$\phi = BA_s + \mu_o H\,(A_c - A_s) \tag{3}$$

where A_s is the cross sectional area of the specimen and A_c the cross sectional area of the coil ($A_c = \pi r^2$). The fact that the specimens constitute part of a complete magnetic circuit means that demagnetizing field effects need not be considered here.

Thus the magnetization of the specimen is obtained from the measured flux ϕ as:

$$B = \phi/A_s - \mu_o H\,(A_c - A_s)\,/\,A_s \tag{4}$$

Except at very low H values or when working with magnetically hard materials the air flux correction is negligible.

The emf induced in a coil due to changing flux is given by:

$$e = N\,\frac{d\phi}{dt} \tag{5}$$

If this emf is applied to the input side of an RC integrator circuit, the output voltage is:

$$E = \frac{N\phi}{RC} = \frac{N}{RC}\int_0^t \frac{d\phi}{dt}\,dt \tag{6}$$

Combining (4) and (6), and ignoring the air flux correction, the B field is given by:

$$B = ERC/NA_s \qquad (7)$$

For the MRL apparatus R = 142.8 kΩ, C = 1.76 μF and A_s = 82.5 mm^2. An additional voltage gain between the integrator output voltage and the B field output sockets on the control panel brings the calibration to 1 volt output equivalent to 1 T of B. This calibration was checked using the well-characterized specimen and found to be accurate to within a few percent (see Robertson, 1990 for a comparison of the MRL and CSIRO results after calibration).

4. Operation

4.1 Drift

Integrator drift is a significant problem in operating the instrument. When working at low field strengths it is important to adjust the drift whenever the H field is changed, and sometimes it is necessary to correct the indicated change in B by taking the drift into account. For example, if the drift is adjusted to zero at a certain H value and the H field is then increased to another value, the B value naturally increases, but the integrator also begins to drift. An elementary method of correcting for the drift is to carry out the following procedure:

(i) Record the starting B value (after correcting the drift so that the B output is stable). Call this B_o.

(ii) Change H to its new value, noting the time taken to do this, and record the new B output voltage, B_1.

(iii) Record the B output voltage again after the same time interval, B_2.

(iv) An estimate for the true change in B is as follows:

$$\Delta B = B_1 - (B_2 - B_1) / 2 - B_o \qquad (8)$$

4.2 Ramp Rate and Lag

The B output voltage lags behind the change in H field when the H field is changing rapidly. This arises from eddy currents in the specimens (which shield the interior of the specimen from the H field), and the time constant of the integrator circuit. Therefore it is important that H not be changed too rapidly, and that a few seconds be allowed between changing H and recording the new B value. The ramp rate variable resistor has been set at a sufficiently low value to avoid large errors when H is under automatic control. When H is being controlled manually it is equally important to limit the rate of change (in fact it is the rate of change of B which is important rather than the rate of change of H). Some examples of the effect of ramp rate and integrator lag are shown in Figures 6 and 7.

4.3 Other Potential Sources of Error

In addition to the problems discussed above, there are four other sources of error which become significant when working at low field strengths.

(i) It is difficult to achieve complete demagnetization (the variac method is inadequate because the variac control does not reduce the voltage all the way to zero).

(ii) The B output voltage has a zero offset of + 4.4 mV.

(iii) The triangle wave form (for the H field) begins at + 1.7 mV and is slightly asymmetric.

(iv) The H ramp begins at -7 mV.

These zero offsets are of little significance when working at high field strengths.

4.4 Procedure for Normal Induction Curves

The procedure for measuring normal induction curves (i.e. the DH magnetic process) is as follows:

(i) Demagnetize the specimens as described in Section 2.5 with the Selector Switch in the "Demag" position, the Integrator Switch at "Reset" and the Compensation Selector Switch at "Run". Return the 2 Hz sine wave amplitude slowly to zero.

(ii) Disconnect the coils (25 pin connector) and set the Selector Switch to "DC". Adjust the H current to zero using the DC Control (read the voltage on the H field output sockets). Reconnect the coils.

(iii) Switch on the integrator and reduce the drift as much as possible.

(iv) Manually increase H (DC Control) in steps and record the change in B, correcting for drift as described in Section 4.1 after each step. Adjust the drift to zero before the next increment.

A set of points along the normal induction curve is obtained in this way. A continuous curve can be obtained on an X-Y plotter in similar fashion, or using the "Triangle" or "Ramp" settings of the Selector Switch, but these can be less accurate because it is more difficult to correct for drift.

4.5 Procedure for the DH $(\sigma\ \bar{\sigma})^n$ Process

This process involves demagnetization, application of a magnetic field H and n cycles of application and removal of stress σ. The procedure is as follows:

(i) Demagnetize and apply the H field as described in Section 4.4. Correct drift.

(ii) Apply stress, recording the change in B at required stress levels or using an X-Y recorder to obtain a continuous record.

(iii) Reverse the loading machine and release the stress, again recording B.

(iv) Repeat steps (ii) and (iii) for as many cycles as required (a stable loop is followed after the first few cycles).

Drift is less of a problem when changing the stress than when changing the field. However, slight adjustments of the drift control potentiometer are usually required throughout the stress cycling stage.

4.6 Procedure for the $D\sigma(h\bar{h})^n$ Process

In this process the specimens are demagnetized, stress is applied and the magnetic H field is then cycled n times from zero to h and back to zero. The procedure is as follows:

(i) Follow steps (i) to (iii) of the procedure for measuring normal induction curves in Section 4.4. At this stage the specimens are demagnetized and the controls are set in readiness for further measurements.

(ii) Apply the required stress. If the specimens were fully demagnetized this should cause no change in B. Small changes are however observed. Large change indicates inadequate demagnetization or non-zero DC magnetic field.

(iii) Apply the required magnetic field h using the manual DC Control. Record the change in B and correct for drift as described in Section 4.1. Reduce the drift as much as possible before proceeding to the next step.

(iv) Reduce the magnetic field to zero. Record the change in B as in step (iii). Adjust the drift.

(v) Repeat steps (iii) and (iv) as many times as required. A stable loop is followed after a few cycles.

4.7 Procedure for the $D\sigma\underset{\sim}{h}$ Process

In this process the specimens are demagnetized, stress is applied and the magnetic field is then cycled between +h and -h. Changes in B during this process could be measured in a similar way to the $D\sigma(h\bar{h})^n$ process, but it is simpler to use the H field triangle waveform (sawtooth). The potential sources of error described in Sections 4.1 to 4.3 should be noted when using this approach. The procedure is as follows:

(i) With the coils disconnected, set the triangle wave amplitude to the required value. This is done using the X-Y recorder with only the H input connected. The Selector

Switch is set to "Triangle", and the Integrator Switch to "Run" to begin the triangle waveform. The amplitude can be measured from the recorder trace and adjusted as necessary using the Triangle Amplitude potentiometer.

(ii) Follow steps (i) to (iii) of the procedure for measuring normal induction curves in Section 4.4. At this stage the specimens are demagnetized and the controls are set in readiness for further measurements.

(iii) Apply the required stress. There should be no change in B (but a small change is usually observed). Large change indicates inadequate demagnetization or non-zero H field.

(iv) Turn the Integrator Switch to "Reset".

(v) Ensure that the X-Y recorder is in readiness, and mark the position of the H-B origin. Record the H and B axis scale factors.

(vi) Turn the Selector Switch to "Triangle".

(vii) Lower the recorder pen.

(viii) Turn the Integrator Switch to "Run" to begin tracing the hysteresis loops.

5. Short Coils

In addition to the standard coils 150 mm in length, a second, shorter set of coils is available. These were wound to enable measurements on a type of steel for which a limited amount (150 mm length) of material was avilable. These coils require different compensation setting (potentiometer turned fully clockwise, i.e. no compensation), and therefore different H calibration. Rather than change settings of variable resistors in the electronics, when these coils are used a scale factor is applied to the indicated H value. The nominal H value should be multiplied by a scale factor of 2/3 to obtain the true (approximately) H value.

6. Conclusion

This note describes the method of operation and calibration of a permeameter constructed at MRL to measure the effect of stress and field cycling on the magnetization of various steel specimens. The various settings and procedures are described in detail. Adherence to these details is an important requirement for achieving reproducible results.

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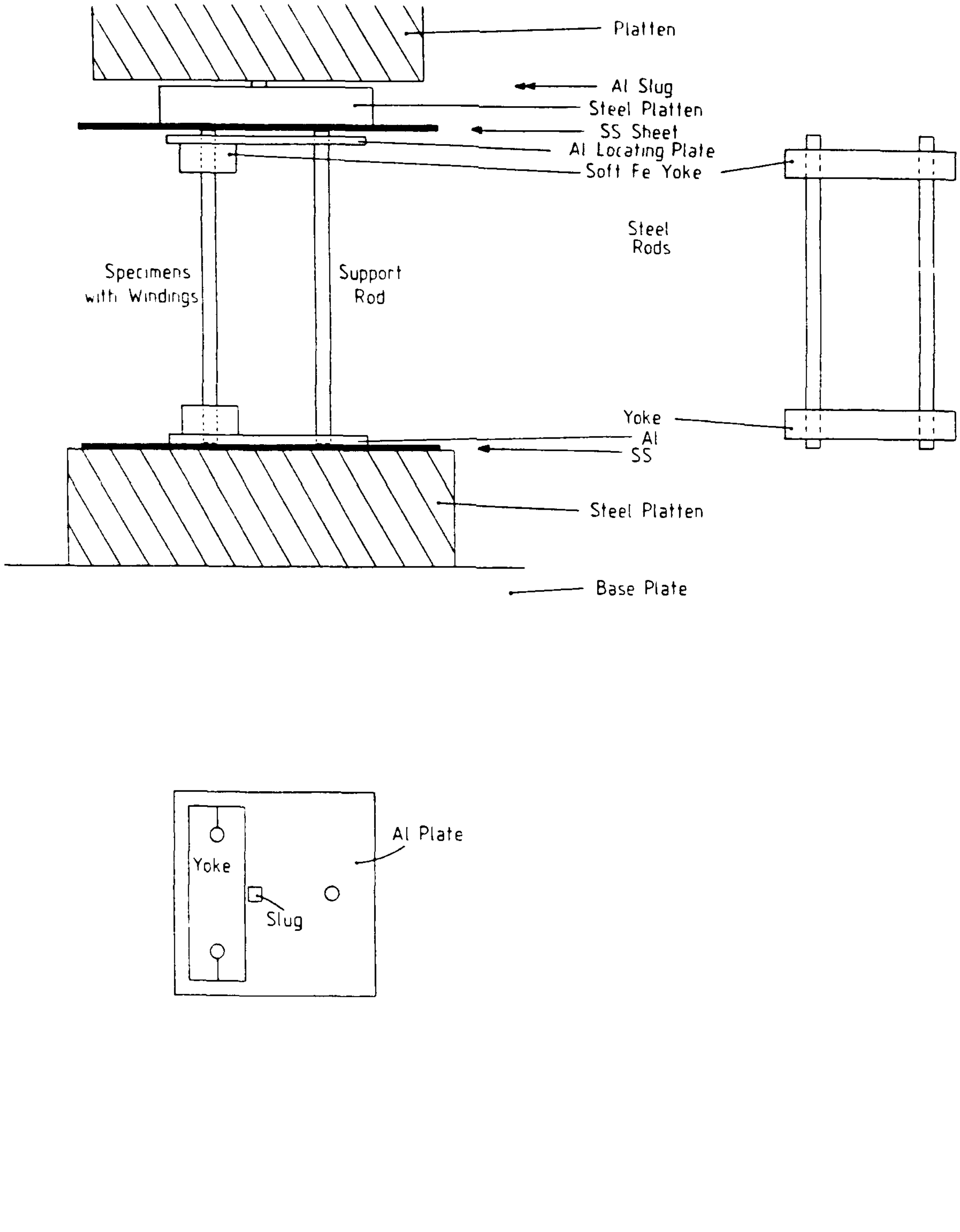

Figure 1 *Elevation, end elevation and plan view of the arrangement for applying compressive stress to specimens during magnetic property measurements. The end elevation and plan views have been simplified for clarity. Stainless steel is designated by SS.*

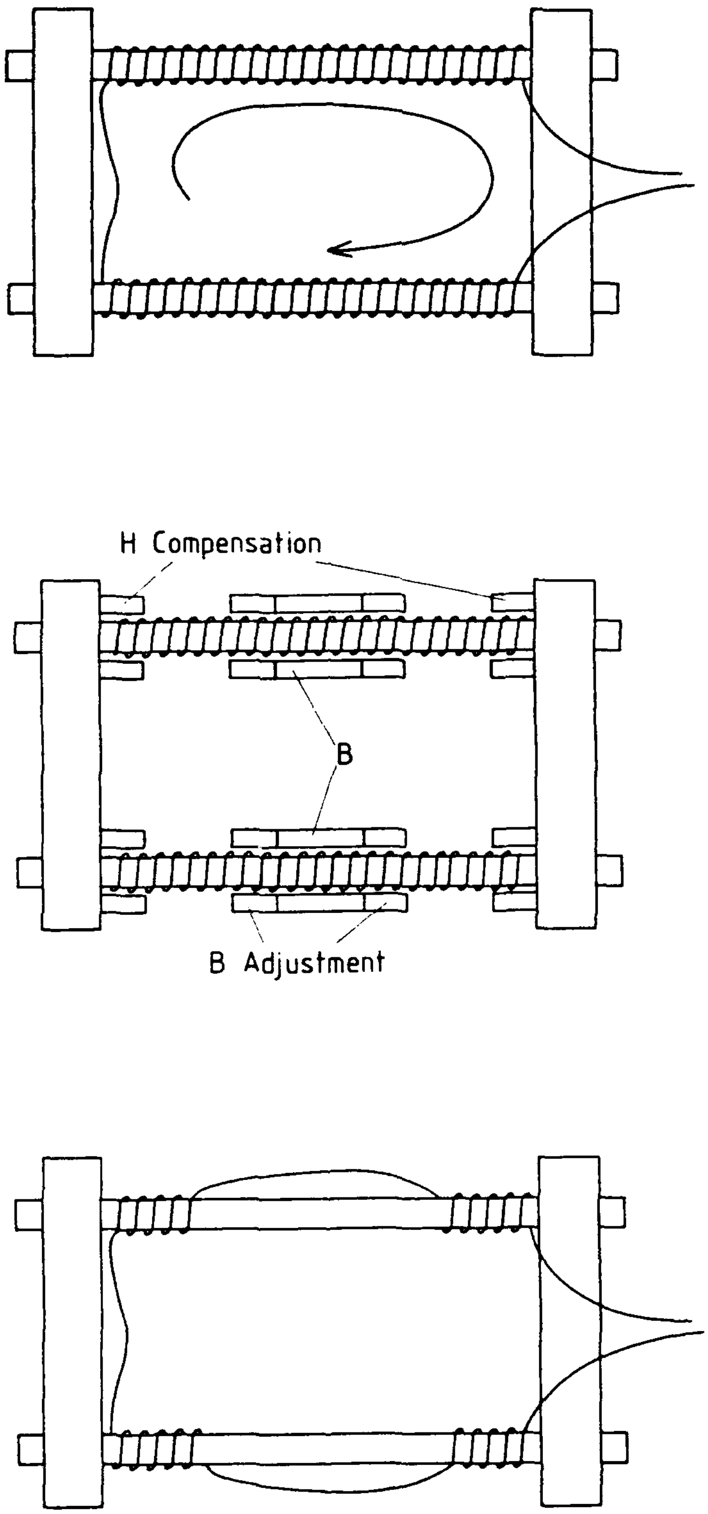

Figure 2 *Arrangement of the coils of the MRL permeameter. The top diagram shows the H windings and the magnetic circuit. The middle diagram shows the locations of the B, B adjustment and H compensation windings relative to the H windings. The bottom diagram shows the H compensation windings. The B adjustment windings are arranged in a similar way.*

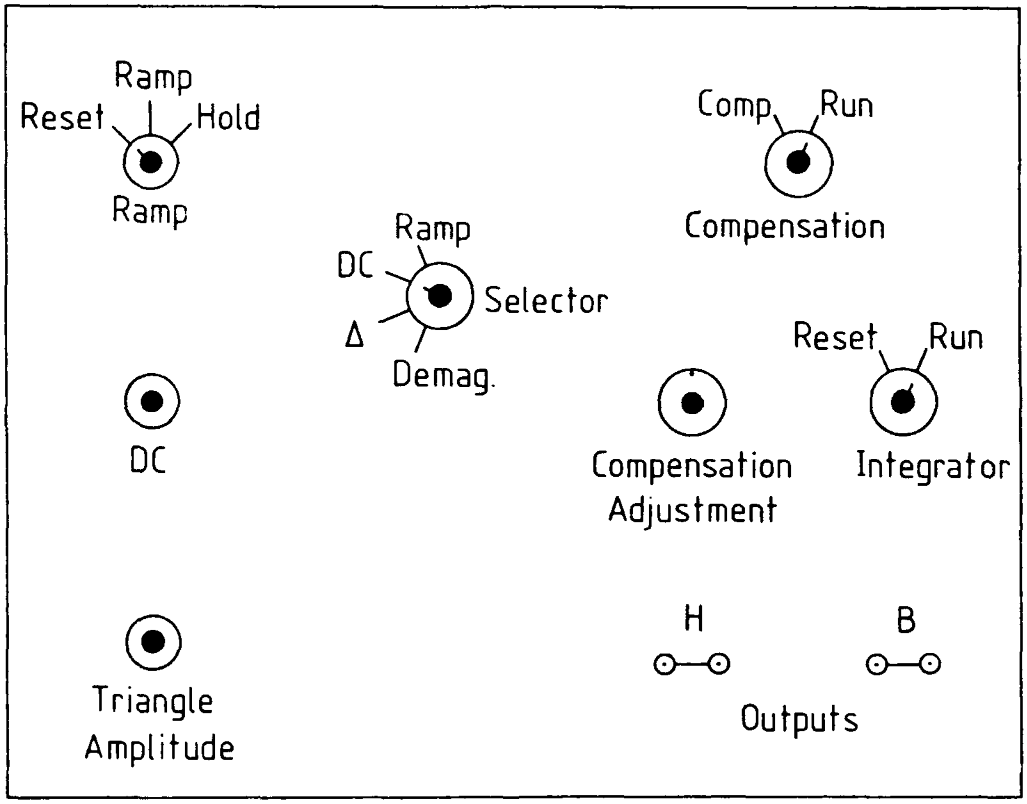

Figure 3 Front panel controls of the MRL permeameter.

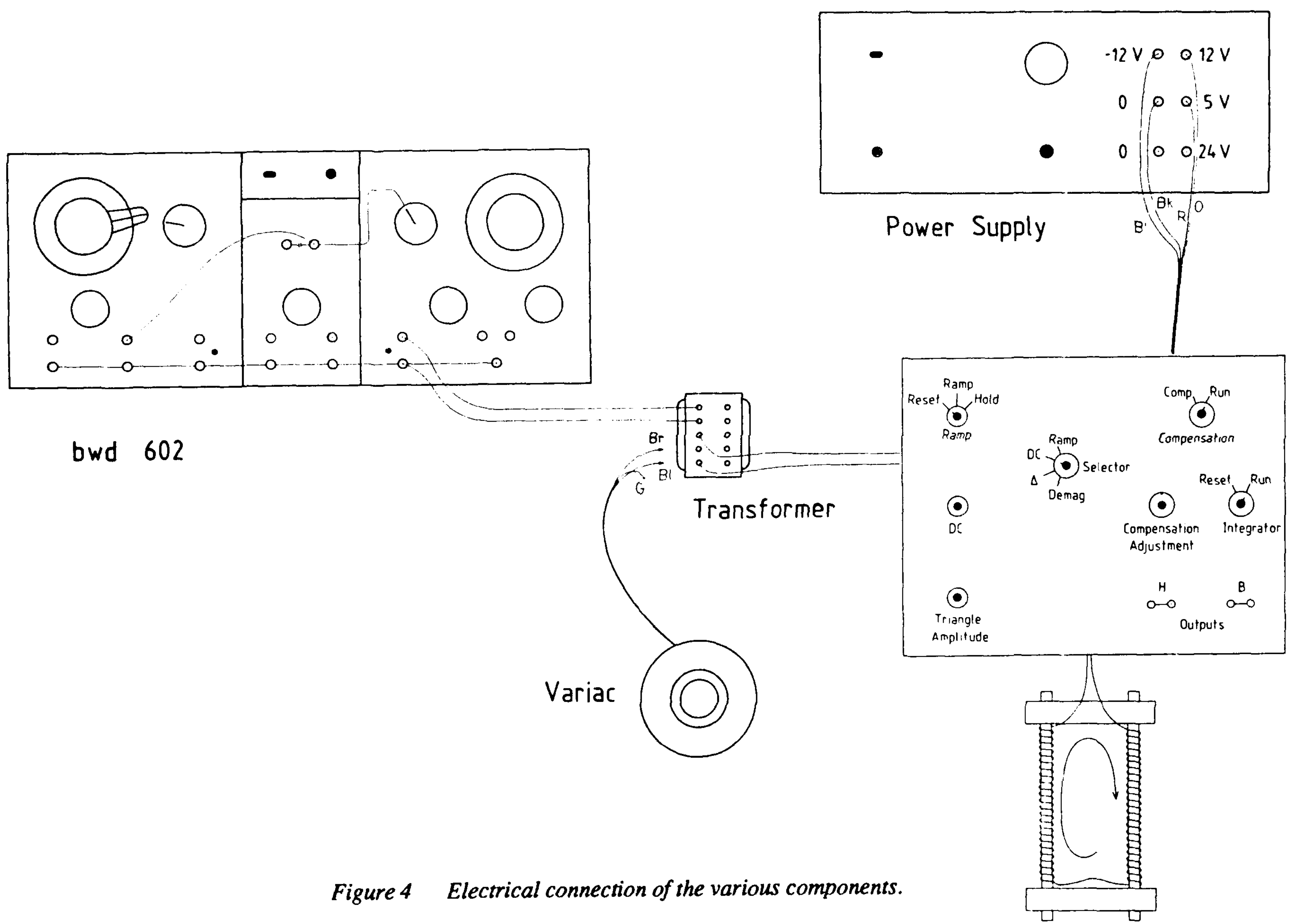

Figure 4 Electrical connection of the various components.

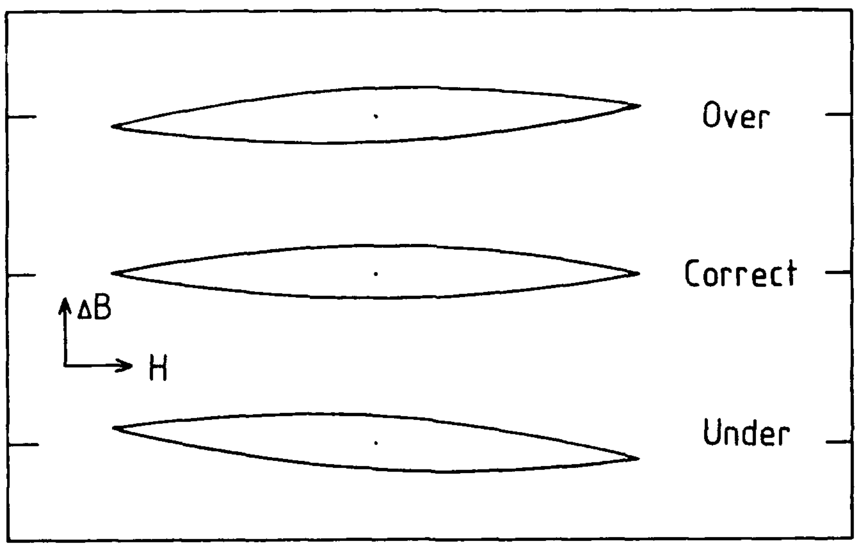

Figure 5 *Hysteresis loops generated during compensation adjustment. Conditions of correct, over- and under-compensation are illustrated.*

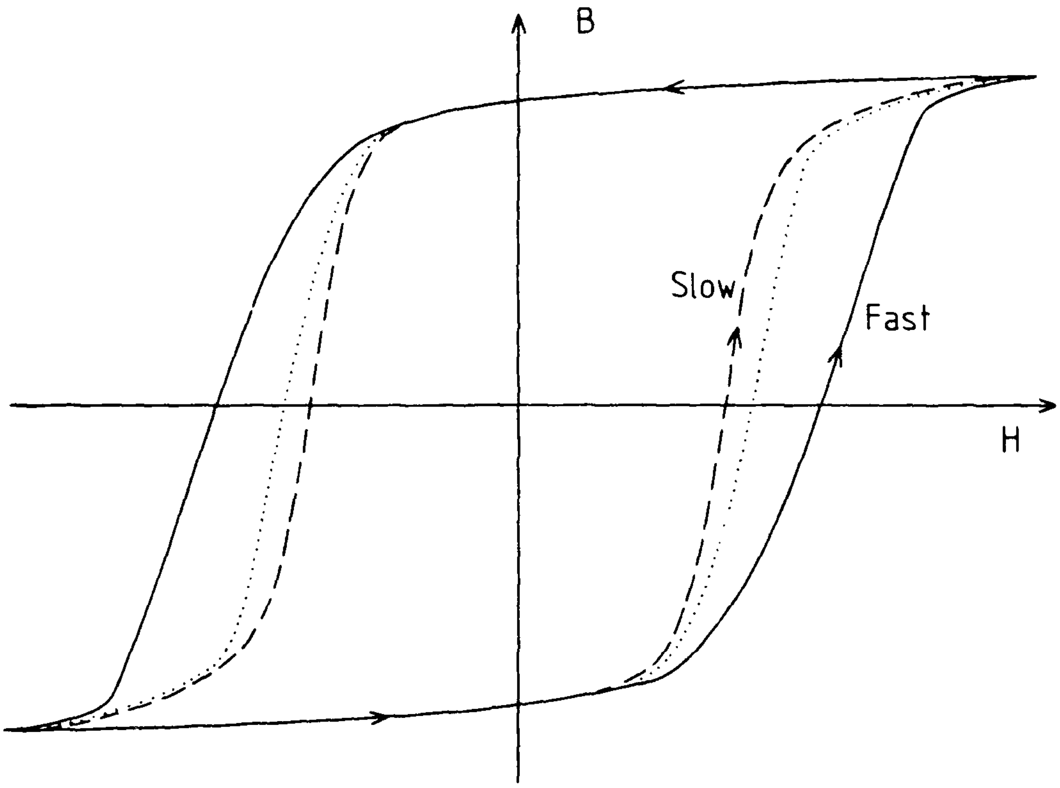

Figure 6 *Effect of sawtooth waveform ramp rate on the shape of the hysteresis loop for a steel specimen. If the ramp rate is too fast, the indicated B lags behind that obtained at slower ramp rates.*

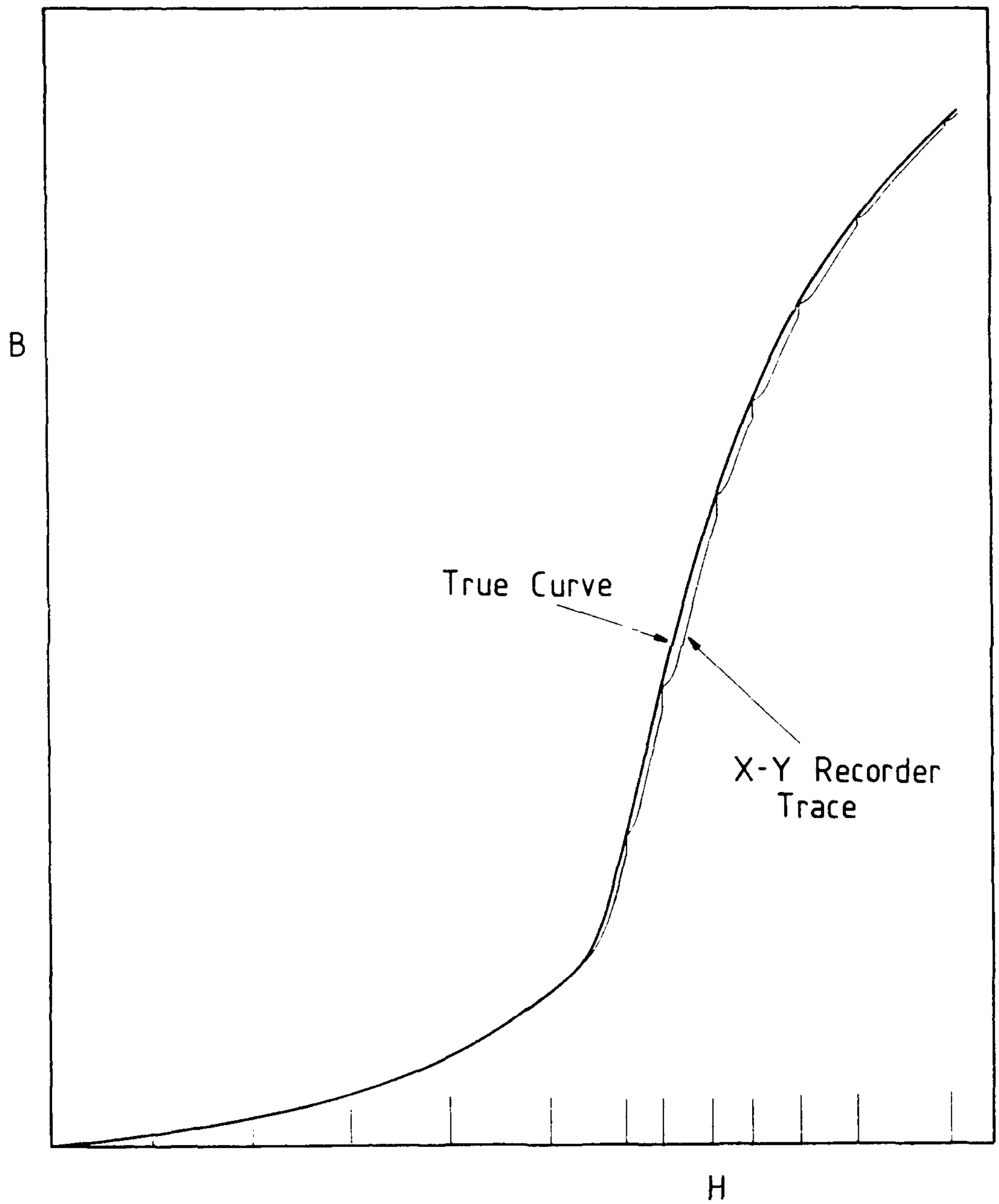

Figure 7 *Effect of integrator lag on the normal induction curve obtained by manually increasing H in steps (the tick marks on the H axis indicate the points where H was held constant to allow the integrator to catch up). Lag is apparent where B is changing rapidly.*

Appendix

Electronic Design Notes on the Permeameter

The electronic design of the permeameter is shown in Figures A1 to A4.

The Integrator (Figure A1):

The present design consists of a buffer amplifier with variable gain and input frequency limiting. The integrator consists of a low input bias current FET input opamp (LF351) with external temperature compensation via a temperature tracking diode.

The variable gain input stage is required because when the permeameter compensation is being adjusted, the input to the integrator is the difference output of the B main coil and the B adjustment coil, i.e. it is the delta flux. This flux is only a small percentage of the total flux and therefore it becomes necessary to increase the sensitivity of the integrator to compensate for the reduced flux level. This is done by increasing the gain on the input stage.

This then leads to integrator drift which is overcome by switching a very large value resistor across the integrating capacitor. While this degrades the integrating accuracy it does stabilize the integrator and in this mode of operation we are more concerned about BH curve orientation than actual value.

Integrator drift is always a problem in this type of equipment and some improvements to the present design are listed below (see Fig. A2).

1. The diode temperature compensation for input bias currents would be more easily adjusted if it was replaced by the arrangement shown in the improved circuit.

2. The compensating diode should be in thermal contact with the opamp and the two devices enclosed in a insulated enclosure.

3. The integrating capacitor should have very low leakage and be reasonably high in capacitance (in order to keep the charge rate from error currents small). The most suitable seem to be polystyrene, polycarbonate, or polysulfone. These type of capacitors are available from Capcom (Adelaide). Even with these capacitors, leakage is a problem, particularly when the voltage across the capacitor is large (leakage current increases as capacitor voltage increases). The solution shown in the improved circuit is to feed back a compensating current proportional to the voltage across the capacitor. This method is detailed in The Art of Electronics by Horowitz and Hill (p. 267).

The Oscillator (Figure A3):

At low fields, oscillator waveform offset and asymmetry become a problem. The offset can be adjusted out, but the asymmetry represents a larger problem as it is caused by the need for the oscillator to run at low frequency in order to avoid errors due to eddy currents in the permeameter. The low frequency oscillator works on the integrating capacitor technique and here again there are problems caused by the capacitor leakage and error currents.

Rather than try to compensate for the error currents a redesign using a digitally synthesised triangular waveform would be a better approach. Advantages using this approach would be easier waveform frequency and shape adjustment, with better stability. Also it would lend itself to being used for specimen demagnetization.

The Power Amplifier (Figure A4):

The existing circuit is straightforward and adequate to drive the present rig. The only point to note is that the transistors dissipate a reasonable amount of power and hence need to be mounted on heatsinks.

Improvements to the circuit would be to -

1. Increase the overall power capability of the amplifier and therefore make it capable of driving the permeameter during the demagnetization phase.

2. The compensation coil adjustment in the present design is adjusted to a fixed ratio of the H coil current. This is not optimal as the loss is not linearly related to the H field. This area of the circuit needs to be changed such that the compensating current can be varied as a function of the specimen magnetization.

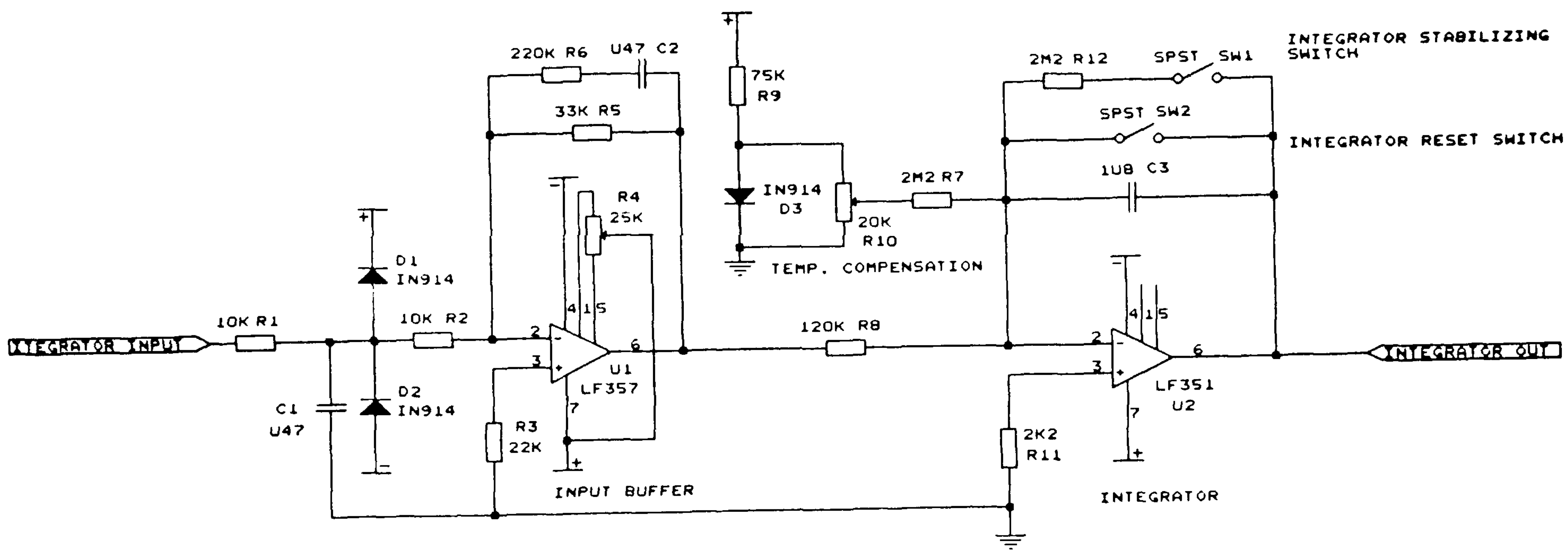

Figure A1 *Permeameter Input AMP and Integrator.*

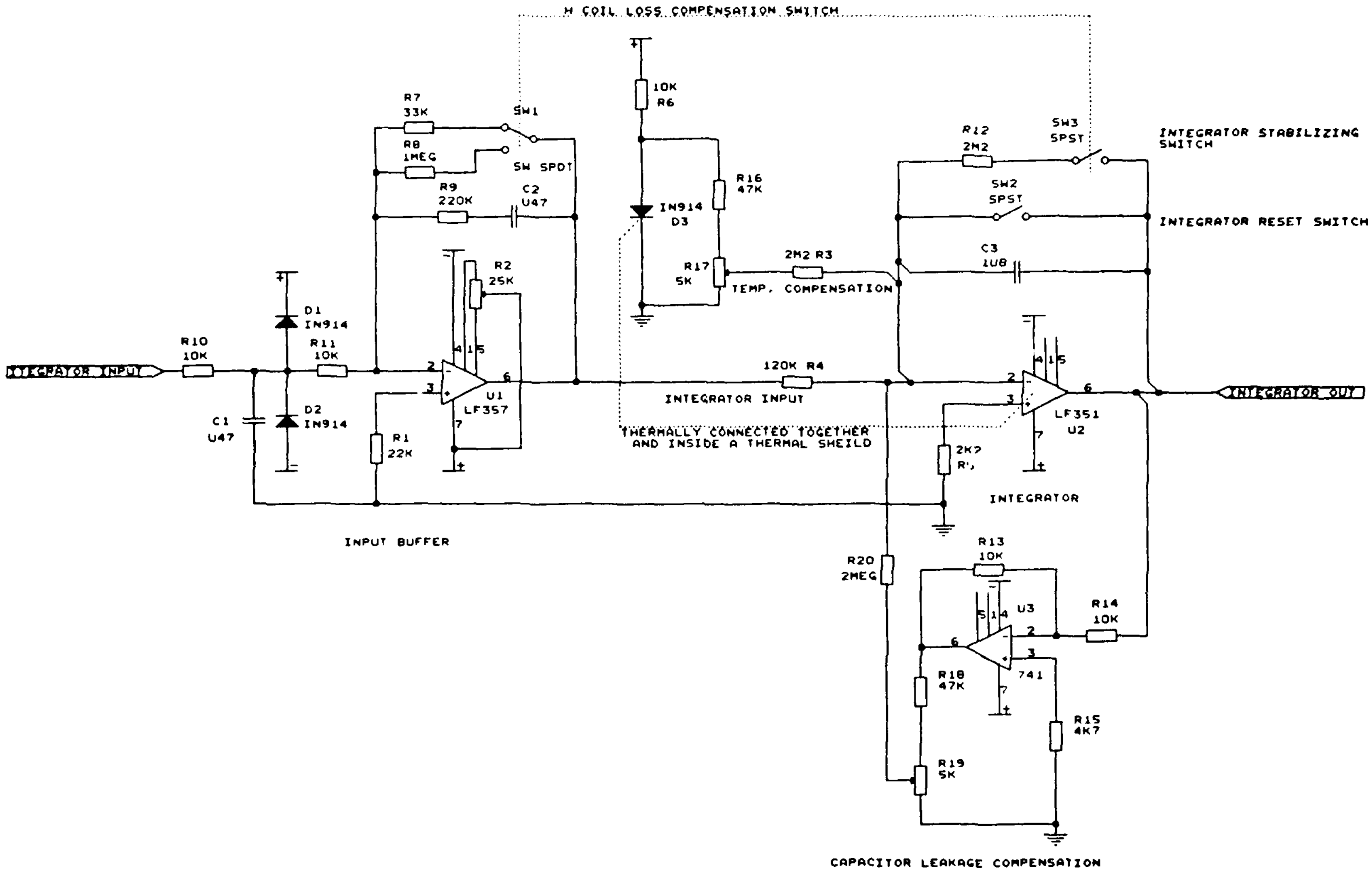

Figure A2 Improved Permeameter Input AMP and Integrator.

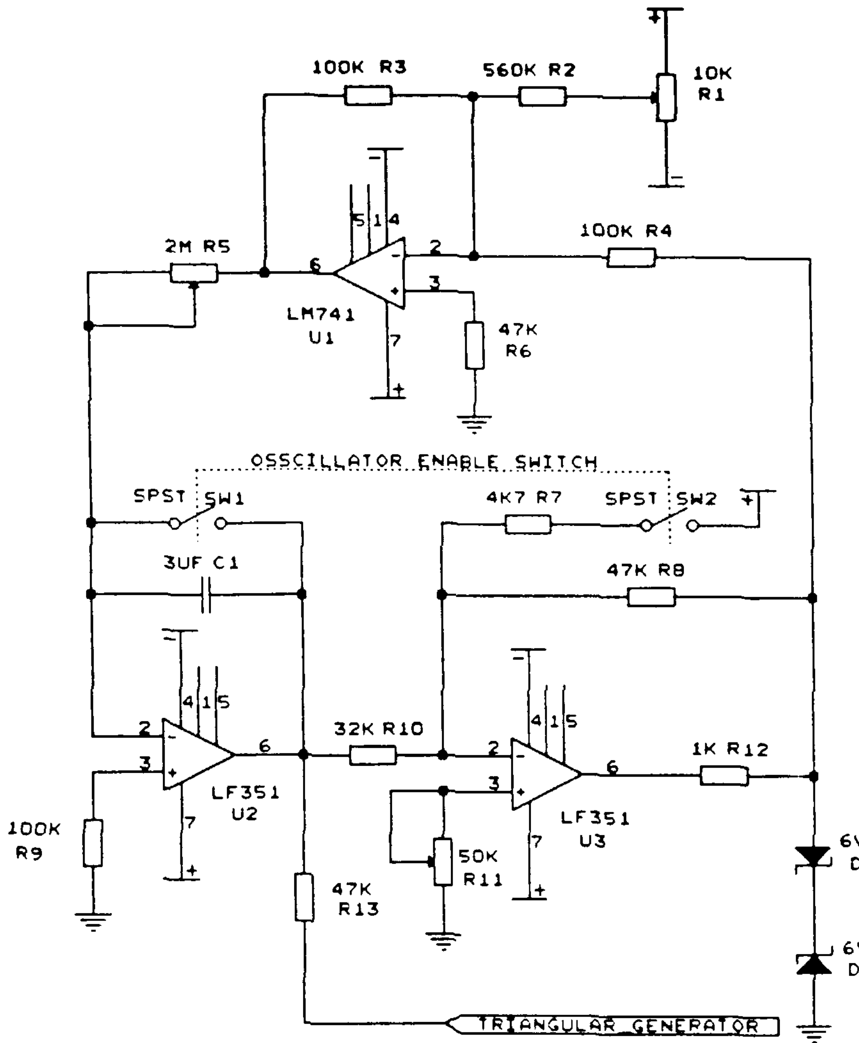

Figure A3 Triangular Oscillator Circuit.

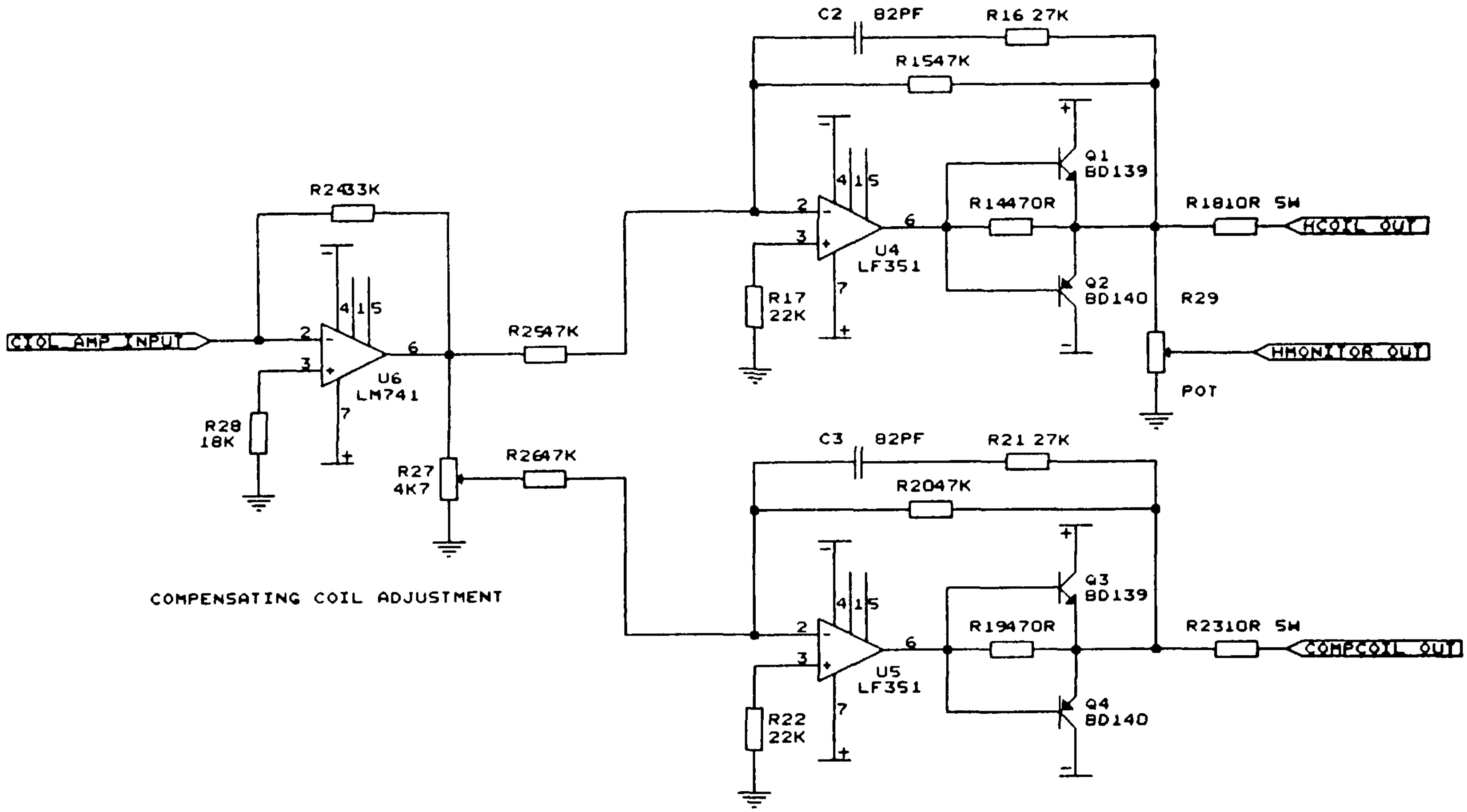

Figure A4 Permeameter Coil Drive Circuit.

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Operation and calibration of MRL permeameter for measurement of DC magnetic properties of materials under stress

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ABSTRACT

This note describes the operation and calibration of experimental apparatus constructed at MRL for the measurement of the DC magnetic properties of steels. The instrument is capable of measuring normal induction curves and hysteresis loops at applied magnetic field strengths up to about 1 kA/m. A special feature is the ability to apply mechanical stress to the specimens before or during magnetic measurements. The stress and magnetic field are applied in the same direction in the specimen, and the magnetic induction is also measured in this direction.